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First quarterly progress report

DEVELOPMENT OF THERMIONIC CONVERTERS

Prepared for
California Institute of Technology
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EOS Report 4018-Q-1

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SECTION 1

INTRODUCTION

This is the first quarterly progress report under JPL Contract 952255. It is a 20-month program to design and develop low-power, high-efficiency thermionic converters of cylindrical geometry. The converters will be capable of being integrated to form a modular power supply. The central philosophy of this approach is to increase the reliability of thermionic space power supplies by redundancy of the basic component.

Seven converters and a bombardment heater unit are deliverable items per the contract Statement of Work. The converter development is to proceed in an iterative fashion whereby each converter design is reviewed separately and approved by JPL before fabrication. Subsequent performance data are reviewed separately, and will formulate the basis for redesign.

SECTION 2

CONVERTER SC-1

2.1 DESIGN AND FABRICATION

Converter SC-1 is a cylindrical converter with an emitter area of 4 cm^2. The converter is designed to operate at an output power density of 4 watts/cm^2 at 0.7V at an emitter temperature of 1400^oC. The designed converter power output is 15 watts. A high-efficiency electron bombardment gun accompanies SC-1 with an anticipated converter efficiency of 10 percent.

Figure 1 is a composite drawing of SC-1 with the high efficiency electron gun in place. The emitter is solid polycrystalline rhenium with a layer of 0.020-in.-thick, vapor-deposited rhenium on the emitting surface. The collector is niobium with vapor-deposited rhenium over the collecting surface. The collector was thermal cycled to 1700^oC, with no deterioration, peeling, or warpage of the vapor-deposited rhenium.

The collector heater wires and cesium reservoir tubulation adaptor were brazed to the collector. Ceramic-metal seals and emitter envelope-lead straps were brazed into the subassembly configuration. The converter subassemblies, shown in Fig. 2, were then welded into the final configuration. Three alignment pins for centering the emitter are shown. After welding the emitter in place, the alignment pins were removed and plugs (shown in Fig. 2) were welded into the alignment pin holes in the collector. Since the majority of the subassemblies were electron-beam-welded into the final converter configuration, some new welding parameters (Table I) were determined from feasibility studies.

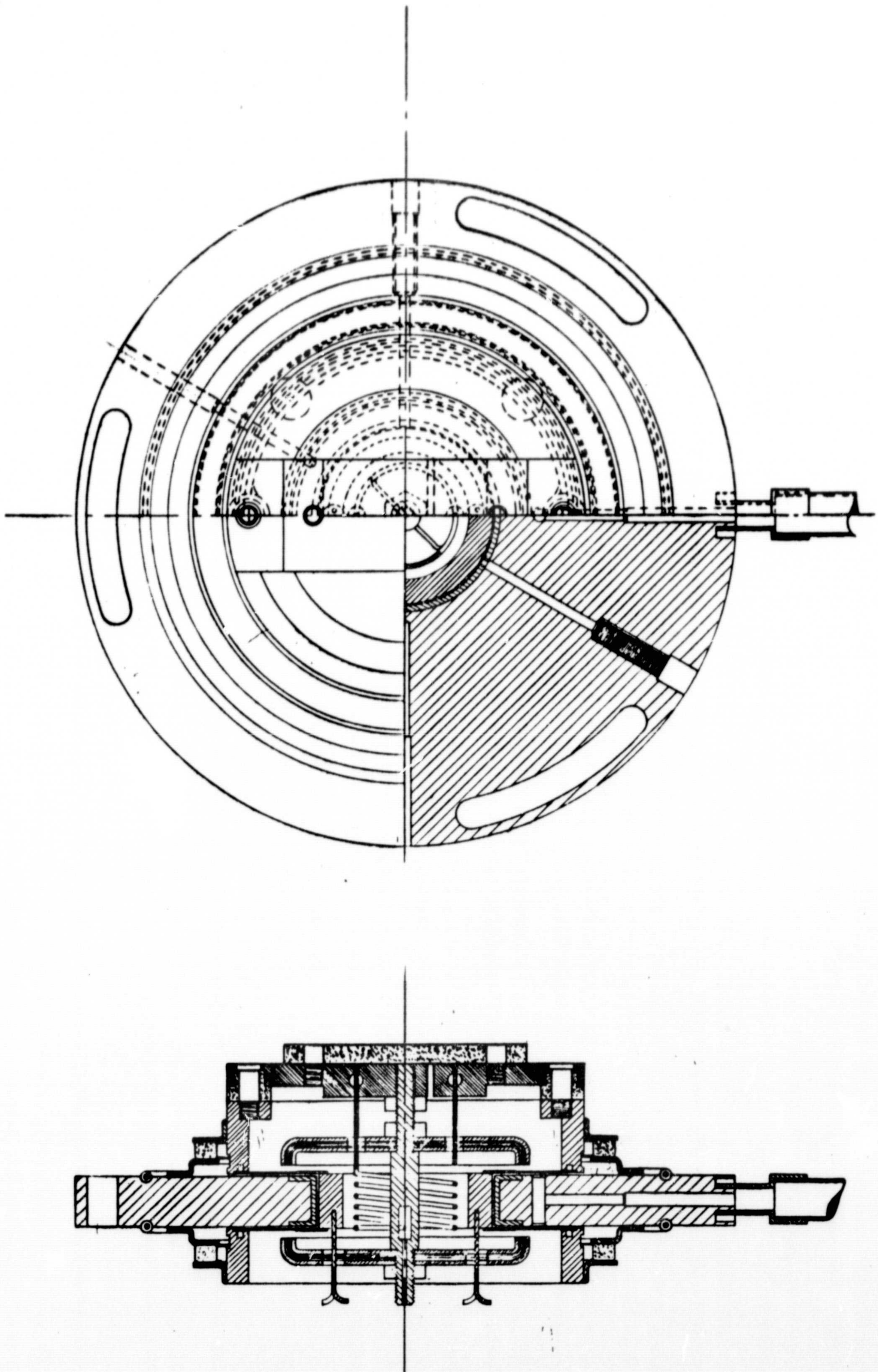

Figure 1. Converter SC-1 and Electron Gun

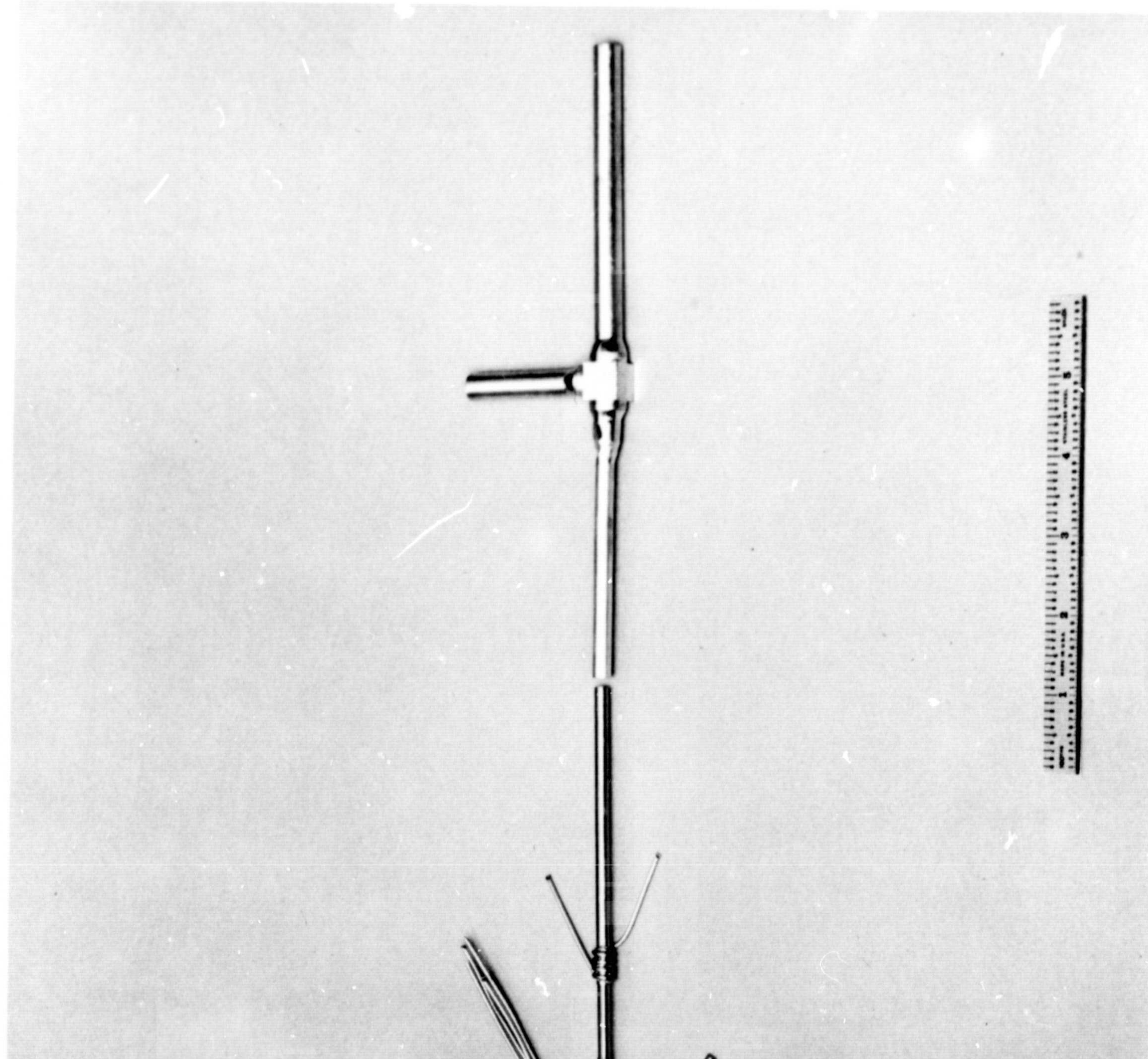

Figure 2. Converter SC-1 Subassemblies

TABLE I

WELDING PARAMETERS

	Filament Current (A)	Accelerating Voltage (kV)	Beam Current (mA)
Collector seal flange to collector	1.75	150	2.5
Emitter flange to emitter lead strap	1.75	150	2.5
Heat choke to emitter	1.75	130	2
Collector plugs	1.75	110	5
Reservoir to collector	1.75	110	2

After completion of fabrication, the diode emitter was heated to 1400°C for 6 hr by electron bombardment until the pressure was 1.8×10^{-7} torr. The cesium loading tubulation was kept at 285°C during the bakeout. A copper pinch-off was then made and the cesium was driven for 1 hr at 300°C.

2.2 PERFORMANCE TEST

The amount of performance testing of SC-1 was dictated to a large extent by an intermittent shorting condition internal to the converter. Data at an emitter temperature of 1300°C and some data at 1400°C were obtained. The shorted condition was prevalent above 1400°C and was unpredictable at lower temperatures.

The shorting appears to be due to deflections of the emitter envelope coming into contact with the collector. This may be caused by residual stresses built up by electron-beam-welding the envelope to the emitter, with subsequent flexure as the emitter and envelope temperatures are varied. In retrospect, the shorting problem apparently can be resolved by repositioning the collector-envelope spacer ceramic.

The converter output voltage (dc) at constant current was optimized as a function of the cesium reservoir temperature at emitter temperatures of 1300°C and 1400°C.

At an emitter temperature of 1300°C, performance optimization was obtained at constant current levels of 20, 30, and 40 amperes, as shown in Figs. 3, 4, and 5, respectively. At 20 amperes, the maximum voltage achieved is 0.29 volt at a reservoir temperature of 280°C. The power output is thus 5.8 watts, giving a power density of 1.45 watts/cm^2.

An approximate comparison can be made with the performance data previously taken with an EOS rhenium electrode variable parameter vehicle with a 2 cm^2 collector.* At an emitter temperature of 1330°C and a cesium reservoir temperature of 281°C, the voltage output is 0.20 volt at 24.5 amperes, giving a power output at 4.06 watts. Since the emitter temperature in this case is 30°C higher than for the case of the converter, the voltage can be adjusted approximately by noting in the reference given in the footnote below that 1°C is equivalent to a change of 0.002 volt. This would mean that the variable parameter vehicle data can be extrapolated as being 0.14 volt at 24.5 amperes for a power output of 3.43 watts at an emitter temperature of 1300°C. The power density is 1.72 watts/cm^2.

Thus, the output of the first 4 cm^2 cylindrical converter is approximately 15 percent less than that of the variable parameter vehicle.

In Fig. 4, at an emitter temperature of 1300°C, a collector temperature of 683°C, and a constant current level of 30 amperes, the optimum voltage is 0.25 volt at a cesium reservoir temperature of 295°C. The power output is thus 7.5 watts.

*A. E. Campbell and D. L. Jacobson, Thermionic Research and Development Program Contract NAS7-514, Final pp. 87, 88, Sept 1968.

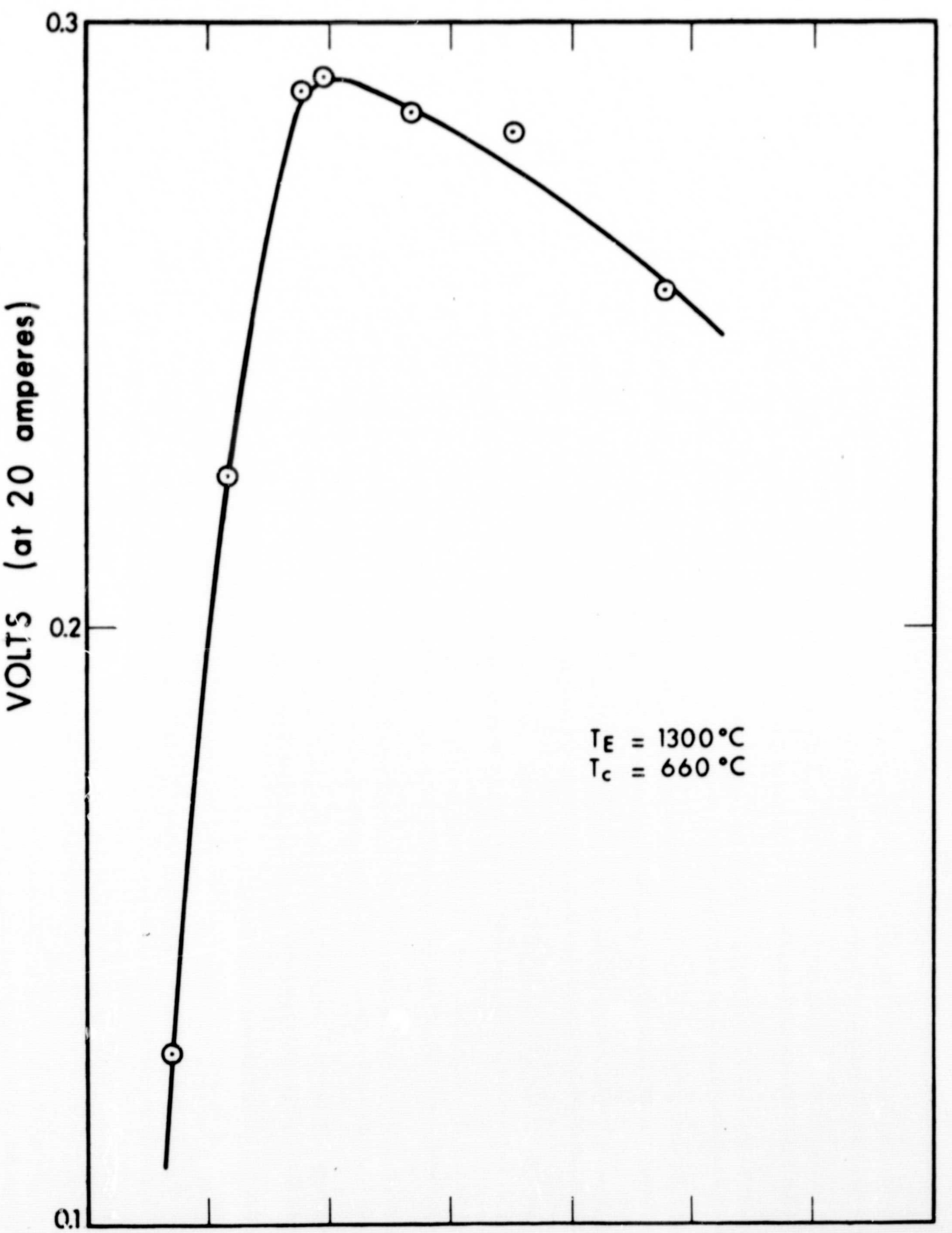

Figure 3. Converter SC-1 Performance Optimized for T_E = 1300°C at a Current of 20 Amperes

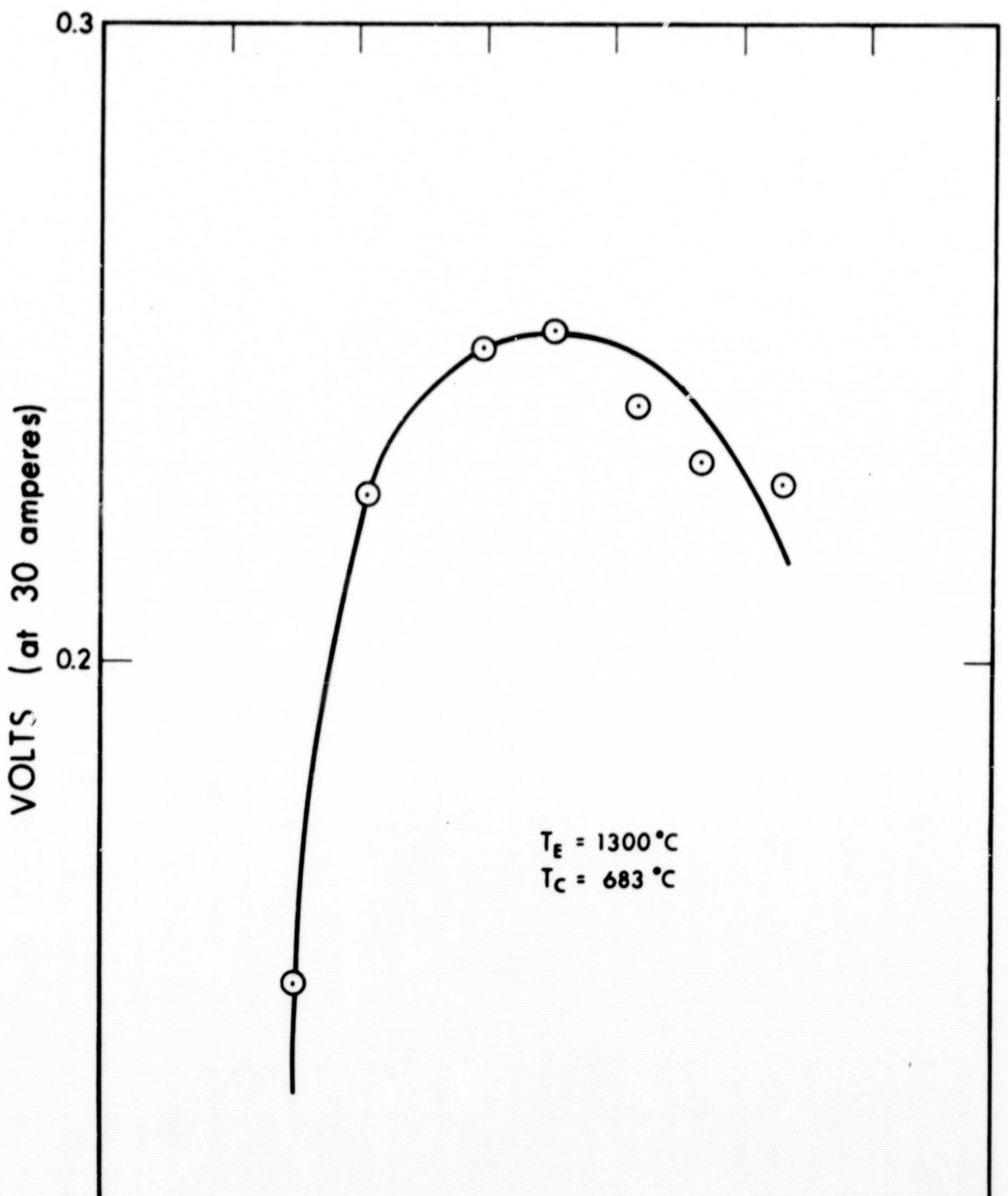

Figure 4. Converter SC-1 Performance Optimized for T_E = 1300°C at a Current of 30 Amperes

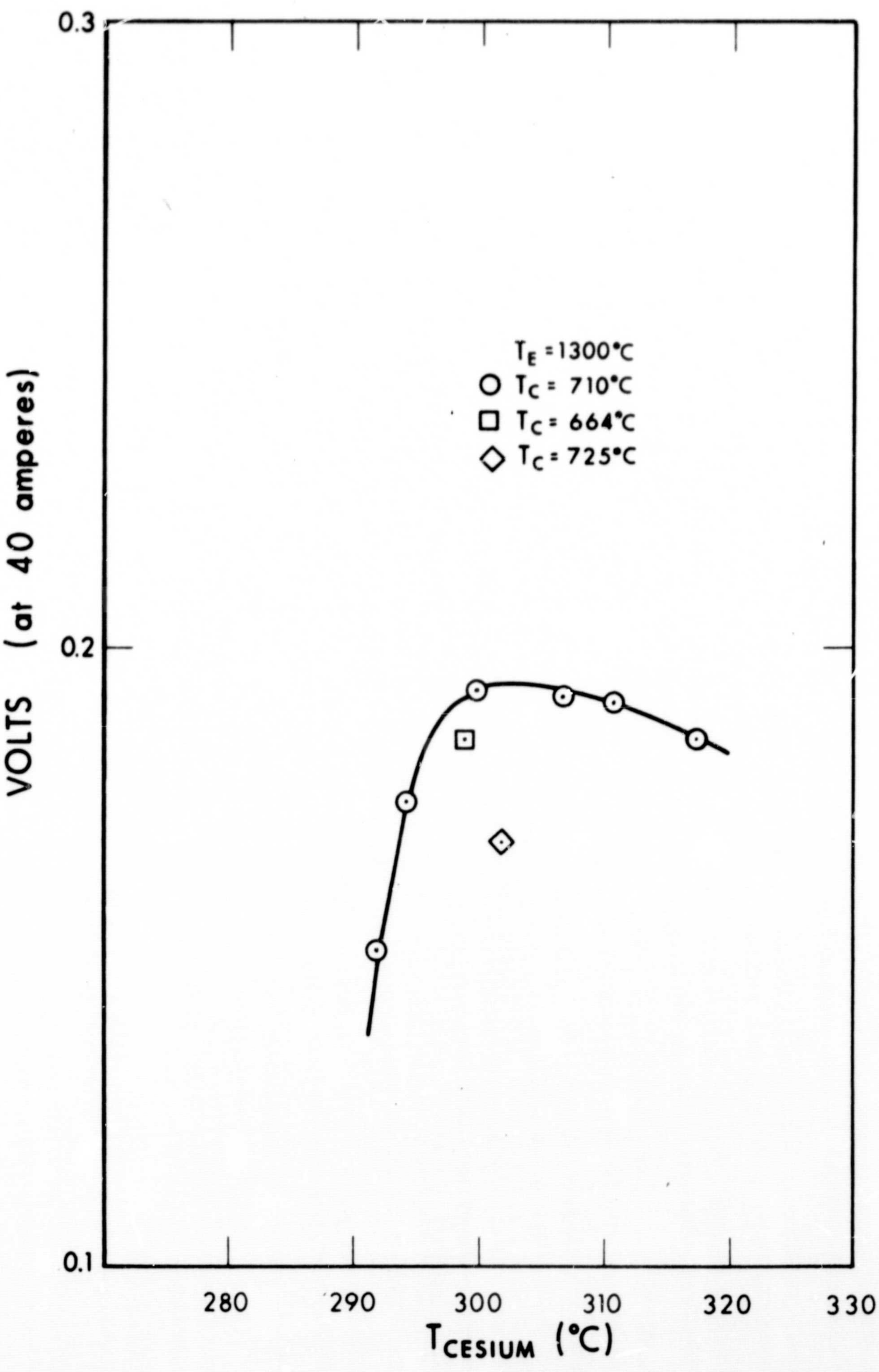

Figure 5. Converter SC-1 Performance Optimized for T_E = 1300°C at a Current of 40 Amperes

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At an emitter temperature of 1300°C and a constant current level of 40 amperes, the optimized voltage from SC-1 is 0.194 volt (7.76 watts output) at a reservoir temperature of approximately 303°C and a collector temperature of 710°C, as shown in Fig. 5. Collector temperatures above (725°C) and below (664°C) the optimized collector temperature of 710°C were used to show that previously optimized collector temperatures for rhenium electrode systems found by EOS are unchanged.*

In Fig. 6, at an emitter temperature of 1400°C, a collector temperature of 738°C, and a constant current level of 40 amperes, the optimum voltage output is 0.295 volt at a reservoir temperature of 304°C. The power output is thus 11.8 watts.

Also observed, at 1400°C emitter temperature and a constant current of 53 amperes, was an optimum voltage output of 0.21 volt, producing a power output of 11.13 watts. It was not possible to produce a full optimization curve at these parameters. This was because of intermittent, internal short circuits attributed to movement of the emitter envelope coming into contact with the collector. Emitter temperatures from 1400°C and above aggravated this condition, prohibiting the acquisition of data at these temperatures.

Figure 7 is a performance plot of the data from Figs. 3 through 6 for the optimized conditions.

Figure 8 is a photograph of SC-1 without the electron gun.

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*Ibid, p. 121, 123

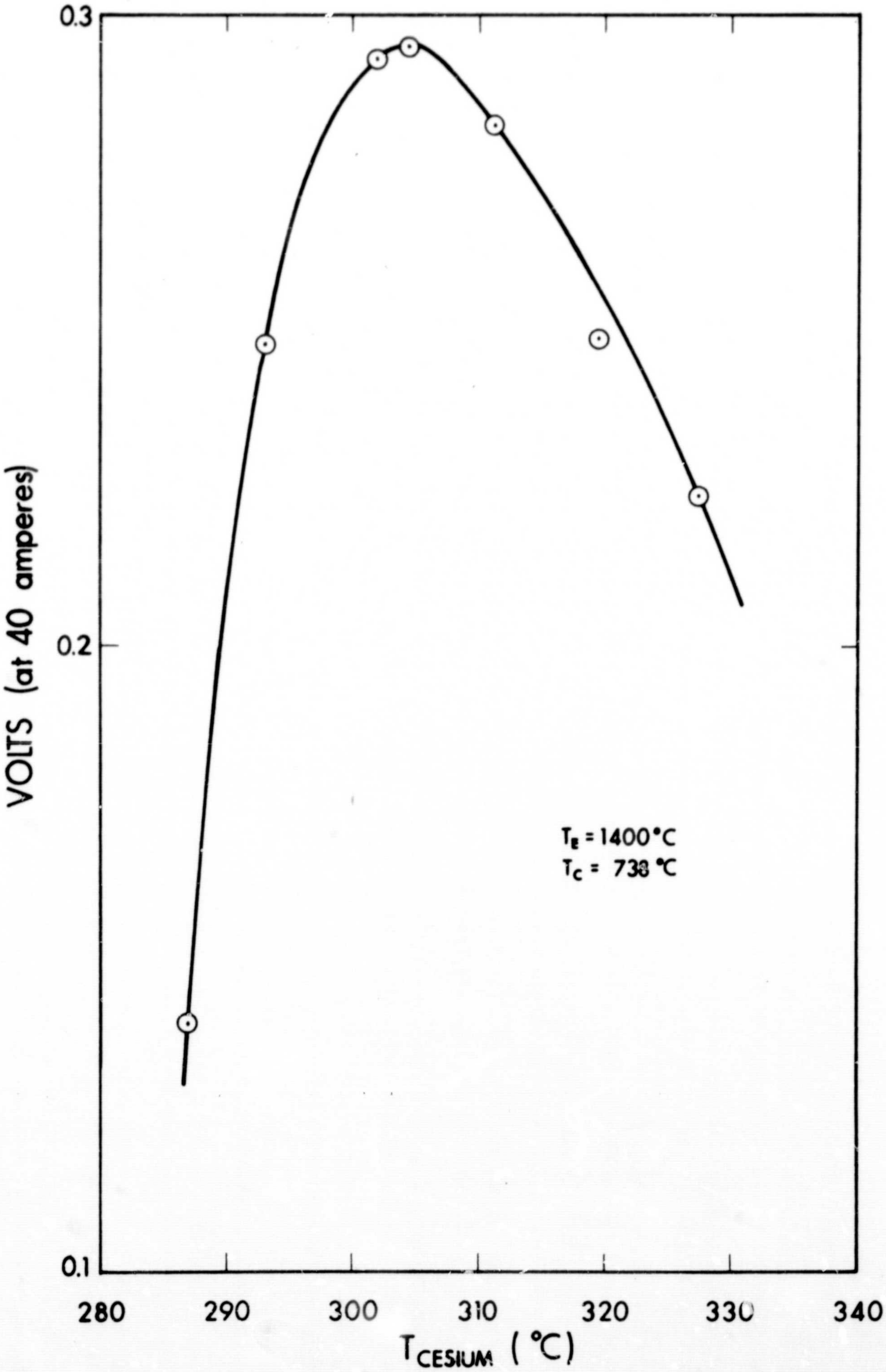

Figure 6. Converter SC-1 Performance Optimized for T_E = 1400°C at a Current of 40 Amperes

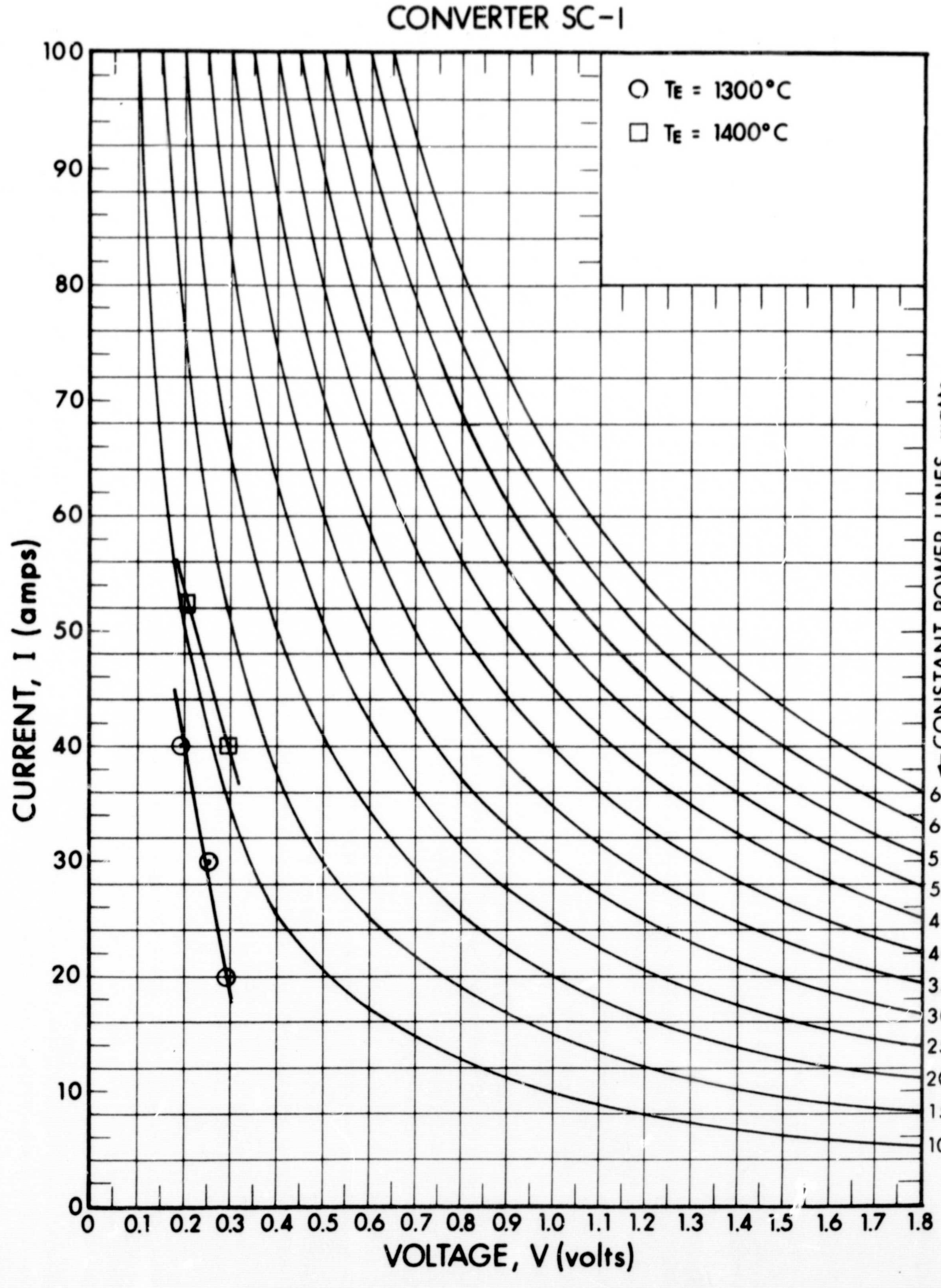

Figure 7. Converter SC-1 Performance Plot

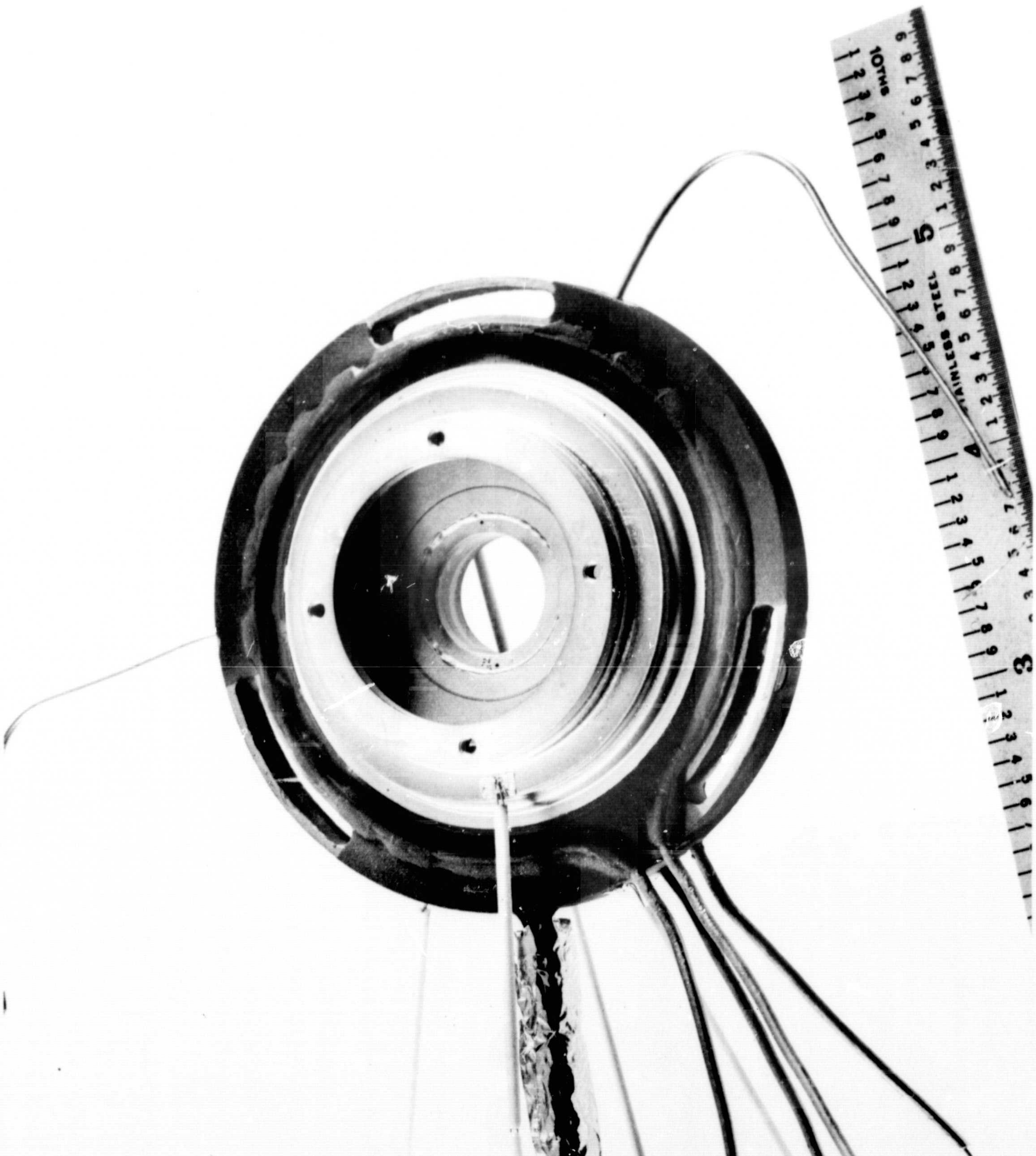

Figure 8. Converter SC-1 After Performance Testing

SECTION 3

CONVERTER SC-2

The design of SC-2 is essentially based upon the performance of SC-1. Special attempts have been made to eliminate the shorting condition experienced in SC-1 by changing from the four small, disk-type, collector-envelope ceramic spacers shown in Fig. 1 to a large, split-ring ceramic shown in Fig. 9, which is an assembly drawing of SC-2. The split ring provides a much stronger emitter support system and is closer to the collecting surface than the disks were in SC-1.

Figure 10 is a drawing of the collector showing the cutout for the ceramic ring. Because of concern that the emitter envelope might exceed safe operating temperatures for the ceramic ring, where contact is made, a piece-wise heat transfer calculation was made to determine the temperature at the point on the envelope where the thickness is heat-choked from 0.010 in. to 0.005 in. This point was chosen to afford a safety factor, as the ceramic does not contact the envelope until at least two mils farther down the heat-choked area.

Conditions chosen for the calculation are as follows: an emitter temperature of 1673°K, emitter lead strap temperature of 963°K (determined experimentally from SC-1 data), constant current of 40 amperes, and a collector temperature of 923°K.

Figure 11 is a sketch of the area of concern. The heat conducted from A to B through the envelope is given by

$$Q_{C(A-B)} = \frac{k_A 2\pi \ell_{A-B} \, (T_A - T_B)}{\ell n \left(\frac{r_B}{r_A}\right)} - \frac{i^2 \rho \;\ell n \left(\frac{r_B}{r_A}\right)}{4\pi \ell_{(A-B)}} \qquad (1)$$

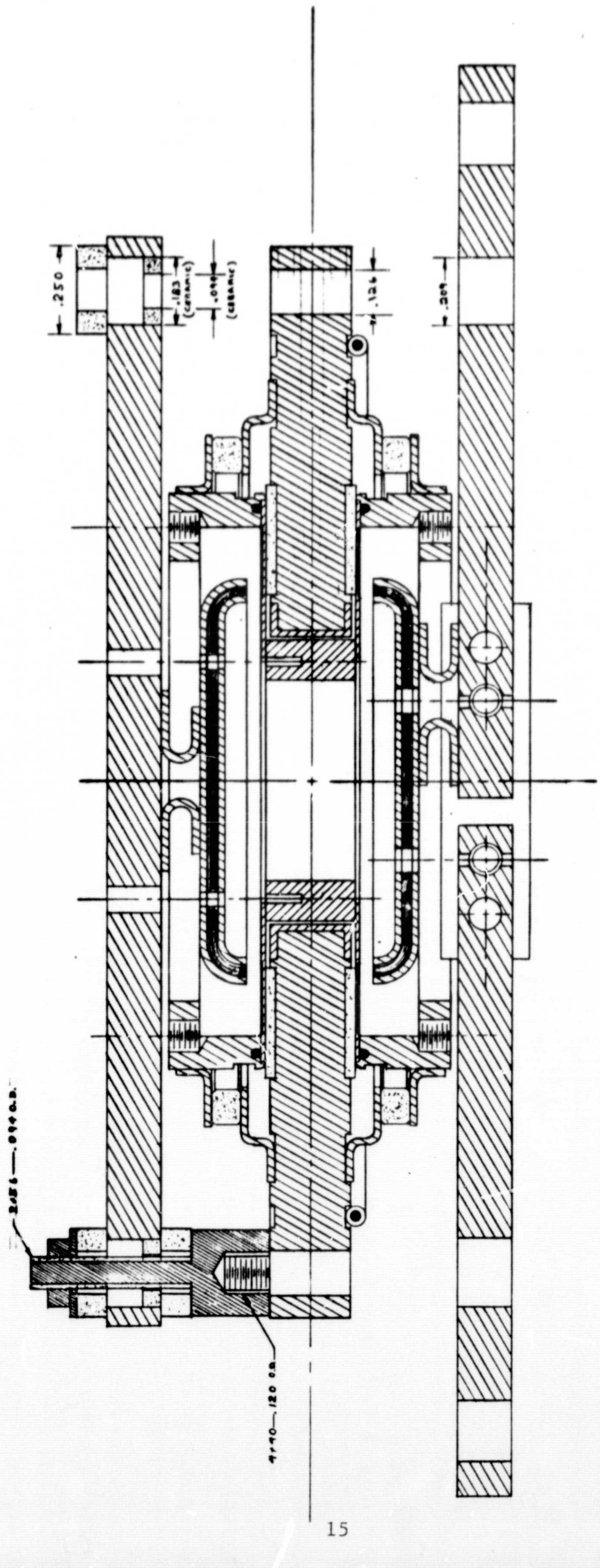

Figure 9. Converter SC-2 Assembly Drawing

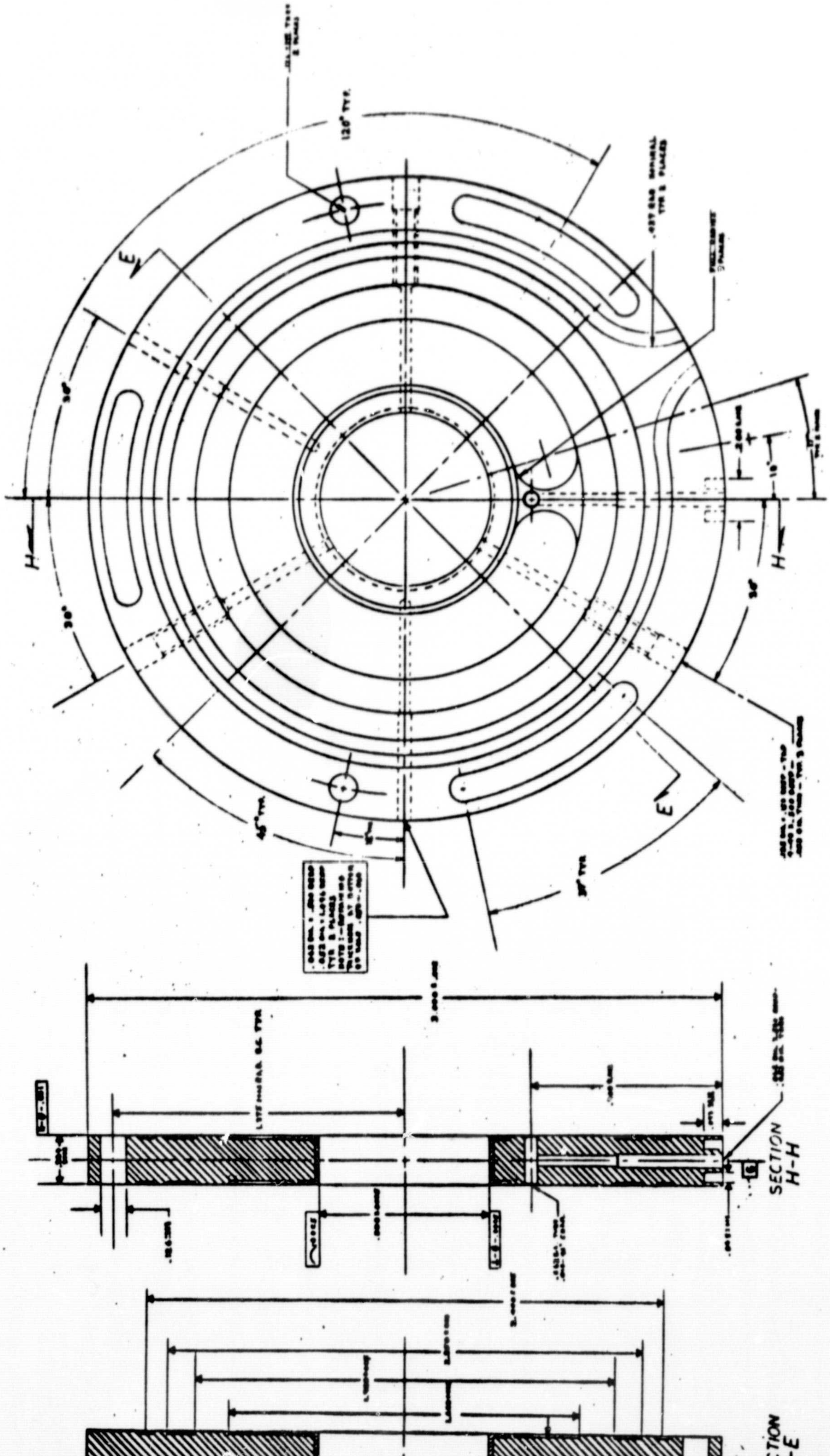

Figure 10. SC-2 Collector

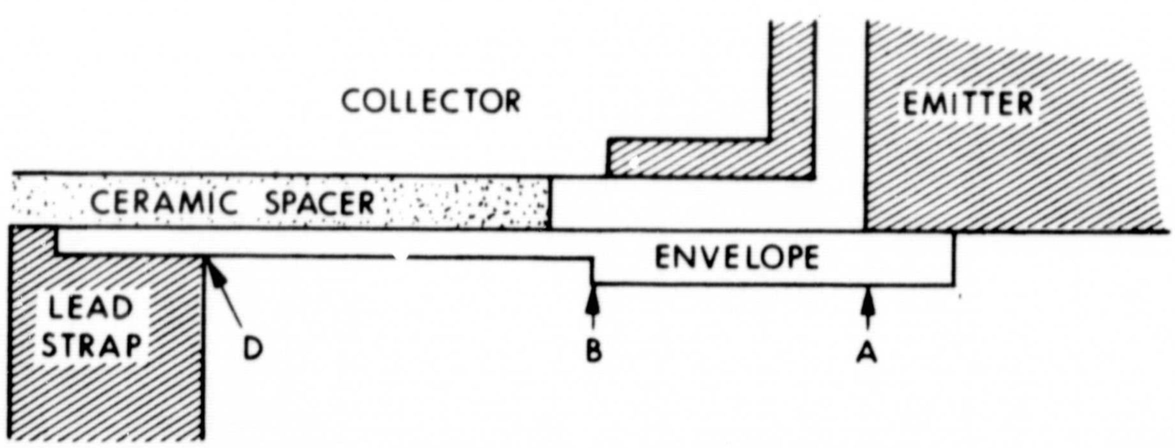

Figure 11. Sketch of Collector-Ceramic-Emitter Area for Heat Transfer Calculations

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where k is the thermal conductivity of rhenium taken at T_A, ℓ_{A-B} is the envelope thickness of section A-B, r are the radii, and ρ is the electrical resistivity at T_A for rhenium.

On the collector side of the envelope, heat is transferred by atom conduction, radiation, and electron cooling. The atom conduction may be estimated by

$$q_p = \frac{\lambda_m (T_A - T_C) A_{(A-B)}}{d + \dfrac{(1.15)(10^{-2})(T_A + T_C)}{P}} \tag{2}$$

where λ_m is a constant, $A_{(A-B)}$ is the envelope area (A-B), T_C is the collector temperature, d is the envelope-collector spacing, and P is the cesium pressure.

The electron cooling term is given by

$$q_{ec_{(A-B)}} = i \left(\phi_A + \frac{2kT_A}{e} + V_m\right) A_{(A-B)} \tag{3}$$

where ϕ_A is the emitter-envelope work function taken at A and V_m is the electron space charge given by

$$V_m = \frac{kT_A}{e} \ell n \frac{J_{sat}}{J} \tag{4}$$

J_{sat} is the saturation current at T_A.

The heat lost by radiation is given by

$$q_{r_{(A-B)}} = \epsilon\sigma (2T_A^4 - T_C^4) A_{(A-B)} \tag{5}$$

where $\sigma = (5.67)\ (10^{-12})$ and $\epsilon = 0.15$.

The term $2T_A^4$ includes radiation from both sides of the envelope.

The total heat lost in the section from B to D can be estimated by Eq. 6, assuming that only the conduction and radiation terms are significant.

$$Q_{C(B-D)} = \frac{k2\pi\ \ell_{(B-D)}(T_B - T_D)}{\ell n \left(\frac{r_D}{r_B}\right)} - \frac{i^2\rho\ \ell n \left(\frac{r_D}{r_B}\right)}{4\pi\ell_{(B-D)}} \tag{6}$$

The radiation losses from B to D are given by

$$q_r = \epsilon\ \sigma\ A_{(B-D)}\ (2T_B^4 - T_C^4) \tag{7}$$

where the factor 2 is to include radiative losses from both sides of the envelope.

The total heat balance from A to D is given by Eq. 8.

$$Q_{C(A-B)} = Q_{C(B-D)} + q_p + q_{ec(A-B)} + q_{r(A-B)} + q_{r(B-D)} \tag{8}$$

From the boundary conditions,

$$q_p = (1.767)(10^{-2}) \text{ watts}$$

$$q_{ec(A-B)} = 101.4 \text{ watts}$$

$$q_{r(A-B)} = 30.4 \text{ watts}$$

$$q_{r(B-D)} = (0.907)(10^{-12})(2T_B^4 - T_C^4).$$

Since T_B occurs in $Q_{C(A-B)}$ and $Q_{C(B-D)}$ to the first power, and in $q_{r(B-D)}$ to the fourth power, in the solution for T_B, $q_{r(B-D)}$ will be neglected to avoid the transcendental equation; in the iteration, the effect of $q_{r(B-D)}$ on the final answer can be determined.

In Eqs. 1 and 6, the thermal conductivity of rhenium, k, is taken to be 0.51 watt/cm ^{o}C, and the resistivity is taken to be 80×10^{-6} ohm-cm. T_B is found to be $1167^{o}K$ by solving Eq. 8. With this value for T_B, an iteration can be made assuming linear temperature gradients between A and B and B and D, solving for T'_B. The temperatures will be T'_{AB} = $1420^{o}K$ and $T'_{BD} = 1065^{o}K$. As seen before, the atom conduction loss is small and will be neglected in the iteration. Under the new conditions,

$$q'_{eC(A-B)} = 97.385 \text{ watts}$$

$$q'_{r(A-B)} = 15.5 \text{ watts}$$

$$q'_{r(B-D)} = 1.995 \text{ watts}$$

Again, solving Eq. 8 with these temperature gives $T'_B = 1206^{o}K$.

A second iteration using T'_B gives temperature gradients of $T''_{AB} = 1440^{o}K$ $T''_{BD} = 1084^{o}K$. Under these conditions,

$$q''_{eC(A-B)} = 97.87 \text{ watts}$$

$$q''_{r(A-B)} = 16.43 \text{ watts}$$

$$q''_{r(B-D)} = 2.258 \text{ watts}$$

Solving Eq. 8 with the temperatures from the first iteration gives T''_B = $1203^{o}K$, showing that the ceramic spacers between the collector and emitter envelope will not be subjected to temperatures which might decompose or otherwise damage them.

Although this method of analysis is not as precise as fin treatment, for example, it is felt that the results yielded are sufficient for the problem at hand.

The electron gun of SC-2 is held in place by supports on the collector. The SC-1 electron gun was mounted on the emitter lead straps. It is felt that the new mounting on the collector will permit future converter-emitter redesigns without affecting the SC-2 electron gun mounting.

The collector of SC-1 received a layer of Rokide-C to raise the emissivity of the radiating area to insure that the collector could be cooled to desired operating temperatures. During the testing of SC-1 it was found that the opposite effect occurred. Because of the very large area provided by the cylindrical geometry, the collector had a tendency to be cooler than originally expected. The following calculations show the approximate heat rejection from the niobium collector without Rokide-C.

The heat input to the collector is given by Eq. 9.

$$Q_c = Q_{eh} + Q_r + Q_{CS} \tag{9}$$

where Q_{eh} is the electron heating of the collector given by

$$Q_{eh} = i_{dc} \left(\phi_C + \frac{4kT_P}{\pi} \right) \tag{10}$$

ϕ_C is the collector work function and T_p is the plasma temperature. The heat transferred from the emitter to the collector by radiation is given by

$$Q_r = \sigma \, \epsilon \, (T_E^4 - T_C^4) \, A_C \tag{11}$$

where σ and ϵ have the usual meaning, and A_C is the collector area. The cesium conduction term is given by

$$Q_p = \frac{\lambda_m (T_E - T_C) A_C}{d + \frac{(1.15)(10^{-2})(T_E + T_C)}{p}} \quad . \tag{12}$$

The following values will be used in determining the heat input to the collector:

$$\begin{aligned} \phi_C &= 1.45 \text{ eV} \\ T_p &= 4000^{o}K \\ T_E &= 1723^{o}K \\ T_C &= 973^{o}K \\ i_{dc} &= 40 \text{ amperes} \end{aligned}$$

Equations 10, 11, and 12 then give the following results:

$$\begin{aligned} Q_r &= 35.9 \text{ watts} \\ Q_{eh} &= 77.32 \text{ watts} \\ Q_{CS} &= 10.00 \text{ watts.} \end{aligned}$$

The total heat input to the collector is thus 123.22 watts.

The collector is shielded from the collecting surface back to the insulator-collector flange. From Fig. 10 the diameter of the flange is seen to be 1.98 in. The problem is to determine the temperature drop from the collecting surface to the flange radius. Since the collector is shielded over this region, only conduction heat transfer will be considered. This is given by Eq. 13, including the joule heating term.

$$\Delta T = \frac{\ln \frac{r_2}{r_1}}{k 2\pi t} Q_T + \frac{i^2 \rho \ln \frac{r_2}{r_1}}{4\pi t} \tag{13}$$

r_1 and r_2 are the collecting surface and the flange radii, respectively, Q_T is the total heat input to the collector, and t is the collector thickness from Fig. 10. The values are as follows:

r_1 = 1.026 cm
r_2 = 2.515 cm
Q_T = 123.22 watts
k = 0.67 watts/cm (for niobium)
t = 0.4826 cm
T_C = 973°K
i_{dc} = 40 amperes
ρ = 4.5×10^{-5} ohm-cm

T_C is the collector surface temperature. The temperature at the flange (at r_2) is determined from Eq. 13 to be T_2 = 919°K.

Assuming that the heat conducted down the collector is ultimately dissipated by radiation, a piece-wise solution is attempted in determining the collector-radiator temperature. The first portion will be taken to 3 cm. The following values apply in determining the temperature at 3 cm by the conduction term:

T_2 = 919°K
r_2 = 2.515 cm
r_3 = 3.00 cm
Q_T = 123.22 watts
k = 0.67
t = 0.4826 cm

T_3 is found to be 908°K. Using $T_3 + T_2/2$ as an average temperature for radiation over this region, the heat radiated may be found from Eq. 14.

$$Q_r = \epsilon \, \sigma \, T^4_{(3-2)} \pi \, (r_3^2 - r_2^2) \, (2) \tag{14}$$

where

ϵ = 0.1 for niobium

$T_{(3-2)}$ = 914°K

σ = 5.67×10^{-12} watts/cm^2 °K^4

The solution of Eq. 14 gives Q_r = 6.66 watts.

In the last section the heat conduction is determined from the following values:

T_3 = 908°K

r_4 = 7.62 cm

Q_3 = 116.56 watts

Solving Eq. 13 with these parameters gives T_4 = 895°K. The radiation over the area from 3 to 4 at an average temperature of 902°K is 12 watts.

Thus, the temperature of the collector-radiator will average roughly about 907°K. The radiator can be reduced in size eventually through a design iteration if it is desired.

The results from the calculations made in this section were used as a guide in the proposed design of converter SC-2. Converter SC-2 will be fabricated according to the ultimate design agreed upon through the design iteration procedure. The performance testing will then proceed, according to the statement of work, at emitter temperatures of 1300°C, 1400°C and 1500°C, at optimized cesium pressures for maximum power output, and at output voltages of 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 volts.